Report No. 5675

PACKET RADIO NETWORK FINAL REPORT
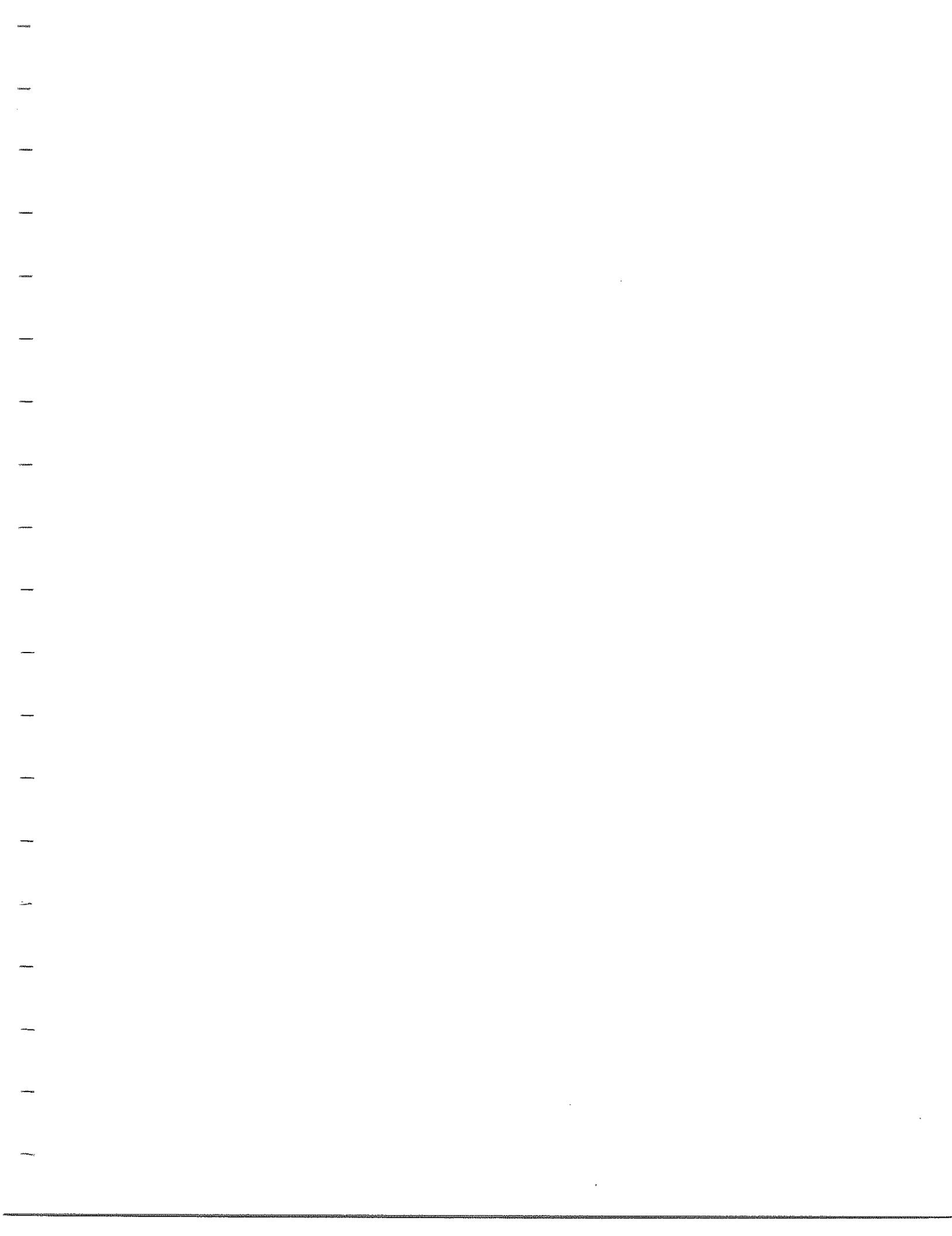

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1. INTRODUCTION

This report describes the work accomplished under contract
MDA 903-80-C-0206. which covered the last three years of the
Packet Radio program.

Over the past ten years, BBN has taken a leading role in the
development of Packet Radio technology. In fulfilling this role
we became the system architects of the Packet Radio program,
creating the Tier and Multistation designs as well as several of
their predecessors. At a more local level, we designed SPP. the
reliable end-to-end protocol used within the network, and we have
significantly contributed to the development of the TCP protocol
used for Internet traffic. We have documented much of our work
in the conference papers enumerated in chapter 2.

In addition. we have implemented the station software. which
controls the routing and distributed name server function in the
multistation environment. To insure adequate system integration
and testing of our software. we have taken a leading role in the
SRI testbed by specifying network configurations and tests to be
run, by implementing network analysis programs. and by leading
the system level debugging of the network. This last role has
fallen naturally upon us because when something doesn't work, the
problem is first noted at the top and must be traced downward.

Our acceptance of the role of system debugger has contributed to
inter-contractor relations as we provided debugging tools, test
scenarios, and on-call advice for any network implementation
problem.

Much of the research performed under this contract was
published as BBN reports and conference papers. The following
chapter provides abstracts of the technical documents.

2.   TECHNICAL DOCUMENTS

During the Packet Radio program, much of the research was
documented first as Packet Radio Temporary Notes (PRTN) and later
published as conference papers. An additional source of
information on the station software is contained in the
operator's manuals.   This chapter contains abstracts for the
technical documents that BBN has produced for this contract.

2.1   PRTNs

The following list of Packet Radio Temporary Notes documents
the history of BBN's involvement in the development of the Packet
Radio network and the gradual evolution of the current software.

PRTN 278, "New PRN Device ID Policy," presents a
redefinition of the device identifier space which permits
graceful exportation of the gateway function out of the station
into a separate machine.

PRTN 279. IEN 120, "Internet Routing and the Network
Partition Problem," describes an extension to routing design in
the Internetwork environment. capable of routing to the correct
partition of partitioned networks.

PRTN 280, "Transfer Points," gives details of the transfer

point, or "incremental," routing, which will permit very long
routes and will support multiple station operation.

PRTN 281, "Multistation Design Specification," specifies how
multiple station operation will work in the Packet Radio Network.

PRTN 285, "Configuring the PDP-11/34 Station for
Auto-Restart." is a guide to reconfiguring station hardware and
its related effects on operational procedure. It was prepared
especially for use at Fort Bragg.

PRTN 288, "Congestion at the PR Hop Level." addresses likely
inefficiencies in the transmission of packets from one Packet
Radio unit to the next under the current protocol. and suggests
particular changes to the hop protocol.

PRTN 289. "Multistation and CAP6 Routing Implementation
Specification," incorporates comments received and negotiated
agreements extending PRTN 281. resulting in a specification for
implementers.

PRTN 289. rev 1. "Multistation and CAP6 Routing
Implementation Specification," is intended to complete the
details required for implementation of CAP6 and to provide some
clarification of network algorithms. A number of technical

modifications were also made. This revision represents a joint effort with Rockwell International.

PRTN 289, rev 2, "Multistation and CAP6 Routing Implementation Specification," represents the completed CAP6.0 design and implementation details. This revision also has updated descriptions of the partially overlapping subnets, CAP6.1, but does not attempt a complete description.

PRTN 290, "Utilizing Internet Routes as Expressways Through Slow Nets," discusses routing traffic through additional, faster networks to reduce delay in delivering the traffic.

PRTN 292, IEN 146. "Flying Packet Radios and Network Partitions." applies the network partition solution. first introduced in PRTN 279, to the problem of airborne Packet Radio units which may be in contact with multiple ground networks simultaneously.

PRTN 295, "Delivering IPR Software to Station Disk," describes the procedure presently used to deliver IPR software to the Packet Radio station disk and documents the necessary support programs and operating environment.

PRTN 300, "CAP7: Station to Stationless Network Interface,"

proposes a major modification to stationless network design which is intended to provide better route assignments with fewer packet transmissions. This PRTN also explores a possible station to stationless network interface based upon the new stationless design.

PRTN 303. "Flooding in Multistation Routing," describes the flooding algorithm used in multistation route setup and explains some of the system requirements for successful implementation.

PRTN 304. "The Multistation Implementation." describes the modules used to perform the multistation function of route setup. The paper also discusses methods of handling errors in route selection and of speeding up route requests.

PRTN 310. "Degradable Performance in Packet Switching Networks." analyzes the behavior of an overloaded packet-switching node with respect to discarding and/or blocking traffic.

2.2 Manuals

This section contains a list of the manuals that can be referred to for information on how to operate the station software as well as for a detailed description of the routing

algorithms used.

"CAP 5.3 Labeler Operator's Guide" documents several new features of the station's Labeler process.

"CAP 5.3 Labeler" describes the operation and internal algorithms employed in this version of the station Labeler process, which receives network status information via the efficient Performance Data Packet mechanism and periodically improves assigned routes and labels.

"CAP 5.6 Labeler" describes the algorithms used to control the CAP5.6 network and to provide routing. Included is the revised Operator's Guide, which documents the new set of available commands.

"CAP 6.0 Labeler" describes the algorithms used to control the CAP6.0 network and to provide routing. Included is the revised Operator's Guide, which documents the new set of operator commands.

"CAP 8 Station Notebook" contains the following information on the CAP8 station.

   o   Overview

o   Operator's guide for the station software

o   Information related to doing a system release

o   Descriptions of how each station process works

o   Manual on XNET, the cross-net debugger

o   Documentation on ELF, the station's operating system

o   Addenda on 11-BCPL, the language used in the station
    software

o   Trouble report form

o   Instructions for setting station identification numbers

o   Description of the station diagnostics

2.3 Conference Papers

The research that was done under this contract was presented
at several conferences. This section contains abstracts of those
papers.

William MacGregor, Jil Westcott, and Michael Beeler,
"Multiple Control Stations in Packet Radio Networks," presented
at MILCOM'82.

Abstract: This paper presents a design implemented by the Packet
Radio Project for control of large networks. The network is
built on a carrier-sense, multiple-access broadcast channel and
is populated with mobile store-and-forward nodes known as Packet
Radio units, or PRs.

Until recently, the Packet Radio network operated with centralized routing controlled by one node, the station. To increase the size of the network and to provide redundant control a multiple station design, "multistation," was necessary.

The PRs gather local connectivity information which is then forwarded to the controlling nodes (stations). Each station is responsible for up to 40 PRs located near it in connectivity and uses these PRs to communicate with other stations.

Questions important to the development of multistation include: How are Packet Radios matched with controlling stations? How do stations find and communicate with each other? How are long routes crossing the borders of many stations determined, and how is their successful setup insured? How is control traffic minimized?

Jil Westcott, BBN, and John Jubin, Rockwell International, "A Distributed Routing Design for a Broadcast Environment," presented at MILCOM'82.

Abstract: In this paper, we present the need for distributed network control in a Packet Radio environment, the criteria used for its evaluation, and an overview of the network algorithms chosen to maintain routing information and to route user traffic.

The routing algorithm, known as tiered rings, functions by
building a distributed tree of shortest path routes to each
Packet Radio in the network. The information kept by each node
grows only linearly as the network expands. The design uses the
radio channel efficiently by providing shortest path routing and
by taking advantage of the information available in the broadcast
environment.

Jil A. Westcott, "Issues in Distributed Routing for Mobile
Packet Radio Networks," presented at COMPCON'82.

Abstract: This paper explores issues in distributed routing
control for store-and-forward networks and emphasizes the needs
of mobile Packet Radio networks. It includes a comparison of the
proposed design for distributed routing in the Packet Radio
network and the routing protocol used by the ARPANET. a wire
network.

In particular, the paper describes proposed modifications to the
distributed routing algorithm developed for the Packet Radio
network. The primary change is in the handling of route failure
due to the creation of route loops or a dead end arising from
loss of connectivity. The purpose of the proposed change is to
speed restoration of the route by making use of additional
information in the neighborhood of the failure. This is

especially important in a mobile environment, because of the high
frequency of altered connectivity.

Michael Beeler, "Degradable Performance in Packet Switching
Networks," presented at COMPCON'82.

Abstract: A packet-switching node becomes overloaded when
traffic arrives faster than the node can service it. We model
such a node and examine its behavior. We identify two regions of
overloaded operation, one where some traffic is discarded and one
where additionally some traffic is blocked. We argue that
discarding traffic is important, and identify parameters a
designer may set to tailor the operation to his particular
network application.

3. MEETINGS AND NEGOTIATIONS

3.1 Meetings

    During this program, members of the BBN Packet Radio project
participated in the following meetings.

   o   Packet Radio Working Group (PRWG) meeting, SRI, December
       4-6, 1979.

   o   Internet meeting, SRI, February 4-6, 1980.

   o   Multistation Implementers Technical Design meeting. BBN,
       March 6-7, 1980.

   o   Second Multistation Implementers Technical Design
       meeting. BBN. April 30-May 1, 1980.

   o   PRWG meeting. Fort Bragg, May 6-8, 1980.

   o   Internet meeting. MIT, week of May 12, 1980.

   o   CAP6 Design Review, SRI, January 26-27, 1981.

   o   Internet meeting. ISI, January 28-30, 1981.

   o   Packet Radio Working Group Meeting. SRI, April 14-16,
       1981.

   o   Internet Working Group Meeting. COMSAT. June 1-3. 1981.

   o   Measurement Design Review, Washington. D.C., June 4-5,
       1981.

   o   Internet Technical Meeting, DARPA, July 8, 1981.

   o   Packet Radio Working Group Meeting, SRI, September 1-3,
       1981.

   o   CAP7 Design Review Meeting. Rockwell, October 8-9. 1981.

   o   Packet Radio Working Group Meeting, SRI. December 15-18,
       1981.

o Internet Meeting, BBN, March 24-25, 1982.

o Packet Radio Planning Meeting, Lake Tahoe, Nevada, April
   19-21, 1982.

o Packet Radio Implementation Meeting, DARPA Headquarters,
   June 8-9, 1982.

o Packet Radio Working Group Meeting, San Diego,
   California, June 22-24, 1982.

3.2 Negotiations

Also during this period. we led negotiations with the other

Packet Radio contractors to achieve or approach closure on the

following design and implementation issues.

o Design and implementation specifications of periodic
   point-to-point route improvement.

o Packet Radio checksumming algorithm design. including
   our running of execution speed tests in a PDP-11
   station.

o Assessment of using seven-hop routes at Fort Bragg.
   resulting in the conclusion reported to ARPA that
   seven-hop routes be adopted.

o Study of the impact of upgrading transfer point design
   for support of multistation; impact was deemed small,
   and packet formats were specified which include all
   fields necessary for both transfer points and
   multistation.

o Assessment of secondary storage capacity (presently
   disk) required by the station, as related to the future
   use of bubble memory; resolved that bubbles are
   reasonable, especially because of reduction in expected
   size, weight, power, and possibly hardware failure rate.

o Discussion of the congestion and load problems
   experienced at Fort Bragg. We recommended that they
   install the CAP5.6 software to improve performance.

o Proposal of a new route loop detection method designed
   to overcome loops undetectable because of action by the
   duplicate filter table.

o Design and documentation of the CAP6.0 network which
   resulted in a joint revision of PRTN 289, "Multistation
   and CAP6 Routing Implementation Specification," with
   Rockwell International.

o Investigation of aberrant PR down load characteristics.
   Study of packet transcripts revealed simultaneous
   loading by two stations. BBN maintained a
   correspondence with Rockwell over several iterations of
   the subsequent design changes and agreed with the final
   proposal.

o Discussion of the stationless design (CAP7) to conclude
   the final details.

4. SOFTWARE DEVELOPMENT

4.1 Station

This section describes the work done on the different versions of the station software and some of the other development work that was done to build the current Packet Radio network.

4.1.1 CAP5 development

We completed the CAP5 software, which handles a single station network with distributed store-and-forward algorithms and point-to-point route assignment by the station.

o   Implementation of the CAP5.2 Labeler was completed. This Labeler periodically requests source/destination pairs from PRs and, if routes are present, transmits the new best routes.

o   Release to SRI of a Labeler which periodically updates labels in addition to routes.

o   Addition of command to print the text of label packets.

o   Addition of command to print the text of new or repaired point-to-point routes.

o   Addition of command to print all routes improved during periodic updating, including source and destination identifiers.

o   Addition of command to print SPP connection state changes, especially helpful in tracking a connection-handling bug.

o   Modification of Labeler to use seven-hop routes. Although by far the largest changes were to the Labeler,

other station processes (connection, XRAY debugger, and
PR down line loader) were also affected. This change,
constituting CAP5.3, was tested and delivered to SRI,
Collins, and Fort Bragg networks.

o   Completion of the mini-station programming and testing,
    and delivery of the CAP5 mini-station software to SRI in
    time for the GALLANT EAGLE military exercise.

4.1.2   CAP6 development

We completed and delivered to SRI the CAP6.2 software for

multistation operation. This was an upgrade to a multistation

design which allowed for longer routes and larger networks.

o   Implementation, debugging, and testing of the completely
    overlapping multistation protocol.

o   Implementation of the partially overlapping design.

4.1.3   CAP7 development

In August 1981, BBN presented PRTN 300, "CAP7: Station to

Stationless Network Interface," proposing both a new stationless

network design and the outline of a design which interfaces

station and stationless areas. At the CAP7 Design Review meeting

in October, the group decided to adopt the "tiered ring" design

proposed by BBN.

The CAP7 design is described in the paper, "A Distributed

Routing Design for a Broadcast Environment," by Westcott and

Jubin, which was presented at MILCOM'82, at Boston, Mass., in

October 1982.

4.1.4 CAP8 development

     We completed and implemented the CAP8 design, which provides

further integration of the combination of multistation and

stationless protocols developed in CAP6 and CAP7 software.

4.1.5 IPR down load software

     Over the years the IPR download software underwent several

changes.

     o The PRLOAD process, and also the system to dump PR load
        images onto station disk, were extensively changed to
        support down line loading of both Experimental (EPR) and
        Improved (IPR) versions of the Packet Radio unit.

     o There was a successful demonstration of down line
        loading PR operating system code, CAP protocol, and
        assorted diagnostics into IPRs.

     o Later the new PRLOAD system was transferred to Collins
        and SRI.

     o We also added a command to print the status of down
        loading and a command to list the names of PR load
        images present on the station disk.

4.1.6 Assimilation of PDP-11 TCP4

     This software was received from SRI and integrated into the

station.

4.1.7 Bootstrap

We implemented a bootstrap using 96-bit leaders for use on
the station and minigateway when attached to a Port Expander.
This was also required for attachment to any ARPANET port after
January 1981.   It was delivered to SRI.

4.1.8 Conversion to SPP2 protocol

We converted all the latest versions of station software
from the SPP protocol to the SPP2 protocol, and coordinated this
conversion and testing of the results with Collins.   Our part of
this task was principally a rewrite of the station's connection
process. but the Labeler. XRAY, and PRLOAD also needed
significant modification.   There were several benefits:

o Performance Data Packets (PDPs) arriving at the station
   in a burst are all accepted. buffered. and serviced.
   Previously. the delay to open a new "listening"
   connection after receipt of almost every PDP caused
   others arriving on the heels of the first to be
   discarded.   Use of SPP2 thus provides more complete
   control information and prevents channel burdening from
   retransmitted PDPs.

o The 20-second timeout, necessary to prevent SPP
   oscillation. no longer exists.   Thus connections to PRs
   can be reestablished as quickly as necessary after a
   transaction is completed.   This achieves smoother. more
   responsive. more efficient network control.   Assignment
   of new, improved, or repaired routes will never be held
   up by the 20-second timeout, as occurred in some cases
   in the past.

o Switching to the simpler SPP2 allowed simplification of
   programs, resulting in a savings of station memory space
   needs.   The connection process shrank in size by about

18

50 percent; some reduction in other processes also
occurred.

o The simpler handling and the space savings permit the
   support of more simultaneous connections between the
   station and PRs (or other devices). Only ten words of
   storage must now be allocated per connection to a PR, so
   on the order of a hundred connections can be maintained.

o The conversion to the simpler SPP2 made implementation
   of multistation operation easier.

4.1.9 LSI-11 Mini-Station

We converted the Packet Radio station software to run on the

LSI-11-based Mini-Station, which is now designed to use one

RXV-21 floppy disk and one Bubble-Tec bubble storage unit.

o We wrote drivers for the 1822 interface (manufactured by
   ACC) and for the RXV-21 floppy disks. In addition, BBN
   completed the changes to ELF. bootstraps. PRLOAD. disk
   drivers. and the SPP2 process. which proved necessary to
   use the floppy disks.

o We assisted SRI in the installation and debugging of the
   bubble storage units.

4.2 TCP and IP

Work was done in several areas for the Transmission Control

Program (TCP) and Internet Protocol (IP).

o Changes to host TCP/IP implementation to support "long"
   1822 leaders and IMP numbers exceeding 6 bits.

o Modification of the TOPS-20 internet user queue facility
   to support single-port protocols such as the new IP4
   version of the XNET debugger.

o Integration of monitor-based Internet Protocol layer
   version 4 (IP4), Transmission Control Program version 4
   (TCP4), TCP Virtual Terminals (TVTs), and TELNET into
   the operating systems TENEX, TOPS-20 release 4 as
   supplied by DEC, and the BBN version of TOPS-20 release
   4. This included testing, debugging and distribution of
   the software.

o Changes to host IP software to support multiple network
   interfaces (Multinet). This included installation of
   algorithms to read a gateway descriptor file as the
   system comes up, determine whether gateways are up or
   down, and permit operator notification when the gateway
   descriptor file is found to be out of date.

o Installation, testing, and debugging of the ICMP
   protocol. This included improvement of the routines to
   listen to host "redirect" and "network dead" messages.

o Implementation and testing of a File Transfer Process
   (FTP) for TOPS-20 and TENEX sites based on version 4 of
   TCP and IP.

o Problem investigation and debugging assistance, eg.,
   installation of extensive packet tracing tools, for
   groups including ISI, MIT, and BBN:

        . checksum errors in reset packets

        . flow control problems such as "silly window
           syndrome" and retransmission strategies

        . connection closing problems in user TELNET

        . connection refusals

        . free storage management problems

        . lock management problems

        . TCP-to-user signals problems

        . TELNET virtual terminals (TVTs) problems

4.3 Gateway

     Another area in which BBN did significant work was gateway

software.

   o Delivery of minigateway software to execute in a true
      minigateway, an LSI-11. Previous version had run in
      PDP-11 machines because of lack of LSI-11 availability.

   o Revised the gateway software to include fragmentation
      and option processing.

   o Concluded gateway development and transferred the
      technology to another BBN group (under separate contract
      to DARPA) for standardization, operational deployment,
      and long-term maintenance.

5. SUPPORT SERVICES

5.1 Station software

There were several areas in which BBN supplied support for
the station software.

o We were responsible for the maintenance and delivery of
   CAP5 and CAP6 versions of station software to testbeds
   at Fort Bragg, SRI, Rockwell and SAC.

o Through cooperation with personnel at Collins Radio, the
   effort to bring their PDP-11 up as a station was
   completed. This effort included consultation and
   writing diagnostics on a disk specially prepared for
   Collins. Having a station at Collins significantly
   speeded software checkout of PR code and permitted joint
   debugging sessions where we connected to their station
   via the XNET debugger. This facility was instrumental
   in fast turnaround of PR software fixes and the
   implementation of seven-hop routes (CAP5.3), SPP2
   protocol, IPR down line loading, IPR performance
   improvements, and IPR memory (PROM) retrofit (these last
   two being Collins' tasks).

5.2 Packet Radio software

We provided reformatting and delivery services for Collins'
PR code at all sites.

5.3 Gateway software

We maintained and delivered a considerable volume of
software. For example, the gateways that fell under our
responsibility included:

o   four ELF-based gateways on Packet Radio networks

o   three ELF-based gateways on the SATNET

o   two mini-gateways on Packet Radio networks

o   four SATNET mini-gateways.

In addition, we had responsibility for delivery of gateway software to:

o   University College London

o   Fort Bragg

o   SRI.

5.4   Demonstrations

BBN supported both field activities at the testbeds and special demonstrations.

o   National Telecommunications Conference (NTC) This effort included modifying the XNET debugger to load the gateway at COMSAT, modifying the gateways to support changes to the catenet configuration. and preparation of a stable internet environment on the test system, BBNF, for use as a demonstration host site.

o   HELBAT This involved LSI-11 Mini-Station development, which allowed mini-stations to be deployed in the HELBAT (Human Engineering Laboratory Battalion Automation Test) exercise at Fort Sill, Oklahoma, in October 1981.

o   Gallant Eagle We provided software support and advice for the deployment of Packet Radio mini-stations in the GALLANT EAGLE exercise, in the week of March 1, 1982.

o   TCP We provided TOPS-20 TCP/IP assistance for the above exercises.

5.5 Debugging Packet Radio network

In general BBN lead the system level debugging of the
network. for example. we participated in the hunt for the cause
of bad PR identifiers (IDs). This was a problem that had been
plaguing the SRI network since spring of 1979. Our contribution
included consultation and two special modifications to the
Labeler process. One printed new IDs. which were often bad ones.
and the PR forwarding them as they arrived at the station. The
second permitted the operator to control point-to-point routes by
optionally disabling the fixing of bad routes.

5.6 TCP and IP user assistance and support

Along with developing and distributing the new TCP/IP
software for the TOPS-20 and TENEX, BBN provided the following
general user-level support.

   o Assisted users at BBN. COMSAT. and ISI in the testing of
      TELNET Programs for the HP3000, TAC. and RT-11

   o Assisted users in the installation of IP and TCP in both
      TOPS-20 and TENEX systems

   o Revised and updated the documentation describing the
      user-level interface to IP and TCP

   o Investigated problems and provided debugging assistance
      to groups at ISI, MIT. BBN. and other user sites.